Probabilistic Evaluation of Carbonation Induced Deterioration in Prestressed Concrete Structures

Sabine Loos and Dr. Abdollah Shafieezadeh

Department of Civil and Environmental Engineering, The Ohio State University

INTRODUCTION

The porous nature of concrete makes it vulnerable to deterioration caused by a structure's surroundings. Carbonation is a form of deterioration caused by the interaction between carbon dioxide and the constituents inside concrete. Carbonation exposes the inner reinforcing steel in a concrete member to corrosion susceptibility, leading to undesirable effects:

- Corrosion increases the internal stresses inside concrete, which causes cracks, and therefore more frequent maintenance repairs during a member's design life
- Corrosion reduces the structural capacity of a member by decreasing the cross sectional area of steel reinforcement. This could cause structural failure, or worse, human injury or death.
- In prestressed concrete structures, corrosion is even more of a concern, since each steel tendon carries significantly greater loads

Figure 1: Concrete marine pile affected by concrete deterioration [1]

MOTIVATION

- Current ACI building code is based on the full strength capacity of steel and concrete and does not account for the effects of carbonation
- Carbonation is expected to have a greater effect for existing concrete structures as atmospheric CO_2 concentration increases with temperature
- Past research mainly investigates concrete carbonation at a material level and does not extend to its structural implications
- Predicting the carbonation impact on structural capacity reduction for reinforced concrete members is expected to provide sustainable and safer design for concrete structures in high risk areas

PRESENT OBJECTIVES

- Obtain comprehensive information on the concrete degradation mechanism and corrosion process in prestressed concrete structures
- Familiarize self with OpenSees in order to simulate effect of carbonation degradation on concrete marine pile
- Develop probabilistic model of degradation process in MATLAB to predict the time to corrosion initiation, and ultimately the total amount of cross-section of the inner steel tendons that has corroded
- All present objectives are being completed in preparation of assessing structural implications of carbonation in the future

DATA COLLECTION METHODS

- Compiled information from previous research on the processes of concrete degradation
- Studied international research groups' reports on methods of concrete deterioration that have been incorporated in European Building Codes [4,5]
- Worked with OpenSees manual and examples to develop understanding of program

SERVICEABILITY MODELING

Service life model consists of two phases as shown in Figure 2

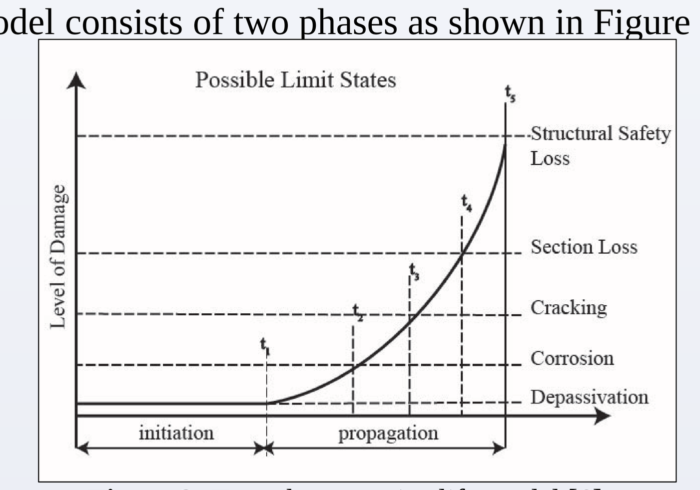

Figure 2: Two phase service life model [6]

INITIATION PHASE: CARBONATION

Factors influencing carbonation:

- Environmental Conditions
- Material Properties
- Design Factors

Carbonation is caused by a reaction between carbon dioxide and CH and CSH in concrete to form solid Calcium Carbonate:

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O$$

$$(3\,CaO \cdot 2\,SiO_2 \cdot 3H_2O) + 3CO_2 \xrightarrow{H_2O} (3CaCO_3 \cdot 2SiO_2 \cdot 3H_2O)$$

A carbonation front forms as reactions progress. The naturally high alkalinity of concrete is destroyed once it becomes carbonated, depassivating the protection around steel reinforcement.

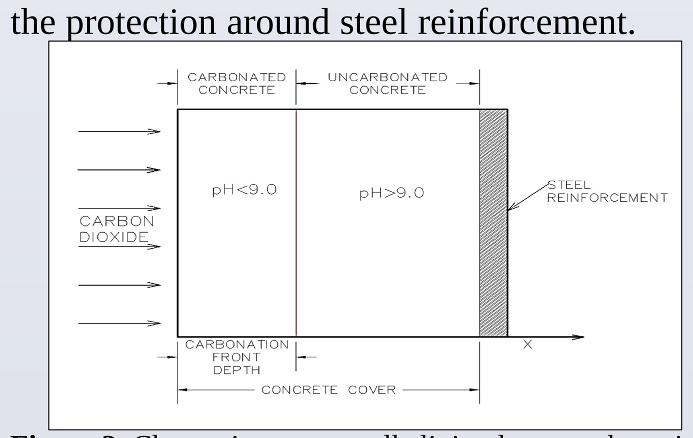

Figure 3: Change in concrete alkalinity due to carbonation

While carbonation destroys the natural steel reinforcement barrier, there are various sources of corrosion: moisture, oxygen, or chloride ingress.

INITIATION PHASE: CARBONATION/CHLORIDE COUPLING

It is rare that carbonation acts as the only corrosion inducing deterioration process, especially in high-chloride marine environments.

- Chloride penetration into concrete induces steel corrosion and the time to corrosion initiation has been shown to occur within 50 years [3]
- Carbonation progresses more slowly than chloride penetration. Therefore, at the carbonation front:
  - Bound chlorides in the concrete are liberated, causing the total chloride content to increase [7]
  - Increased density of concrete causes chloride diffusion to reduce by 20% in carbonated concrete [2]

PROPAGATION PHASE

The propagation phase for the scope of this research will ultimately extend to structural safety loss, or failure of a concrete member.

- The first step in the propagation phase is steel corrosion
- Under chloride penetration, it has been experimentally verified that pitting corrosion occurs, as opposed to uniform corrosion [3]

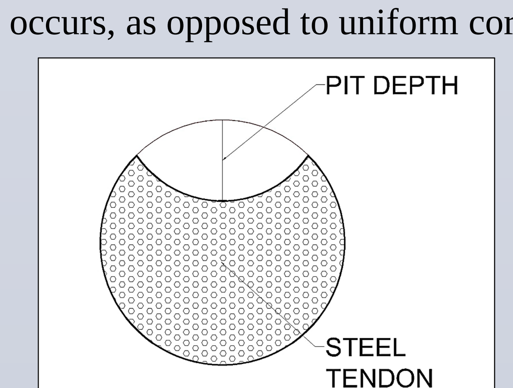

Figure 4: Pitting corrosion in steel tendon due to chloride penetration

3 PHASE ULTIMATE SERVICE LIFE MODEL

1. Probabilistic model of the initiation phase: carbonation progression coupled with chloride penetration
2. Commence propagation phase with probabilistic model to analyze corrosion pit depth
3. Determine time to ultimate limit state using OpenSees FE model of concrete marine pile (Figure 5)

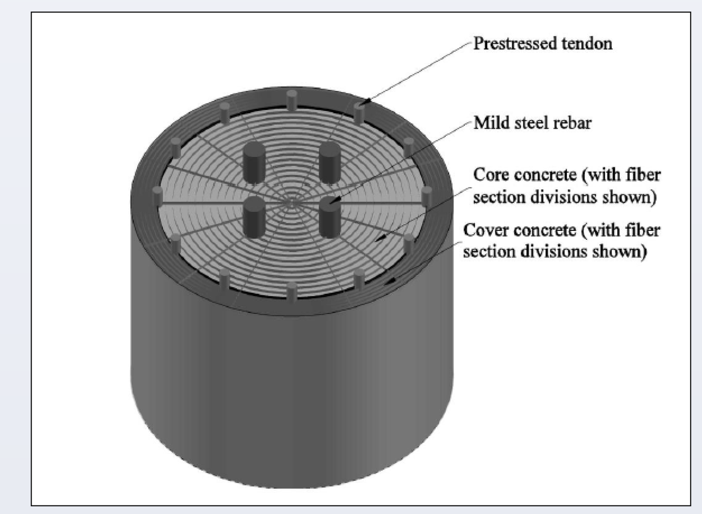

Figure 5: Geometric representation of concrete marine pile modelled in OpenSees [3]

PROBABILISTIC MODEL

- **Reasoning:** Probabilistic models account for inherent stochasticity in variables affecting carbonation and chloride penetration
- **Framework:** Model 1 will model the depth of chloride penetration until it reaches the face of the steel reinforcing tendon with an inner moving boundary for the carbonation front (Figure 6)

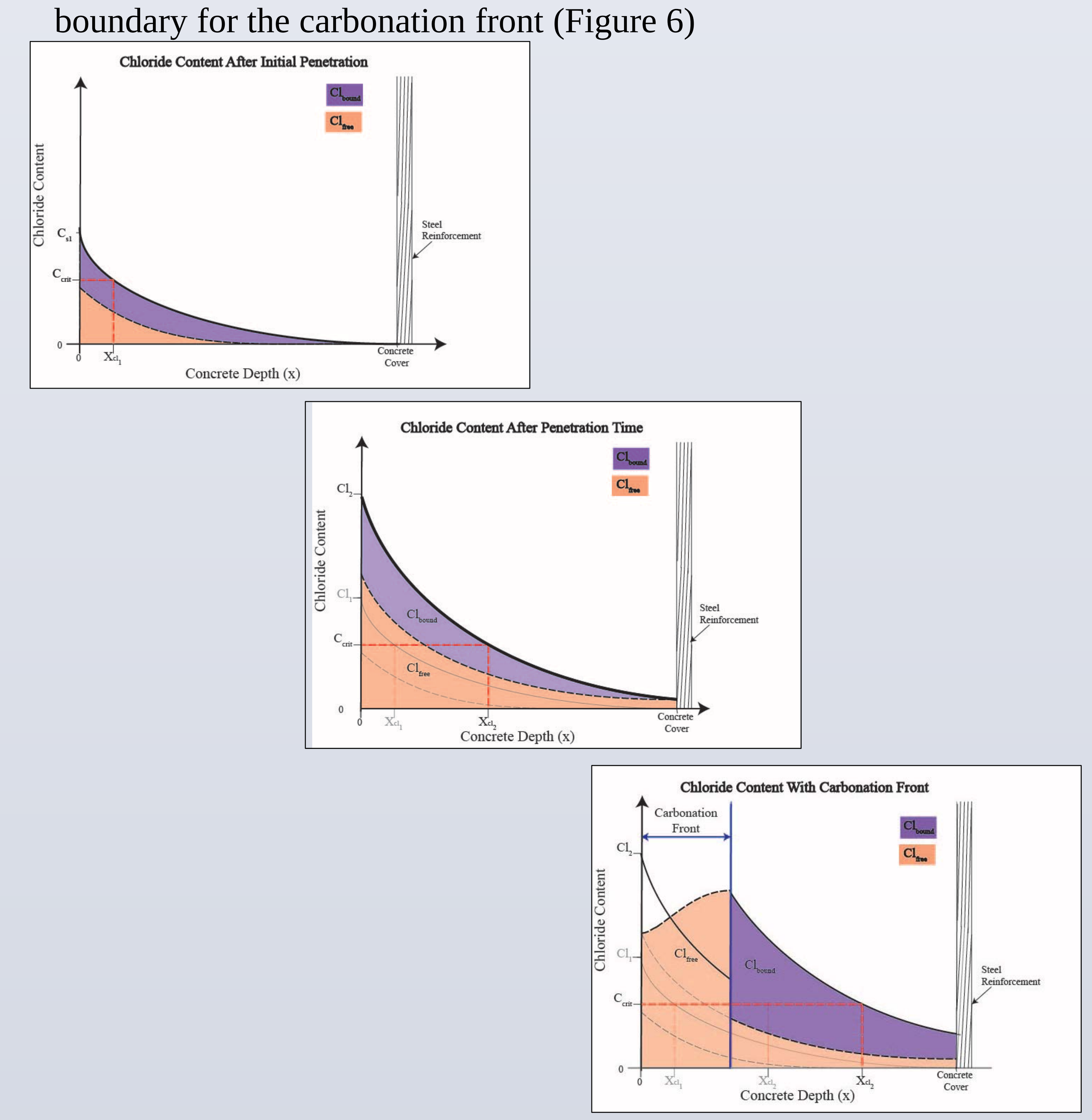

Figure 6: Representation of Chloride and Carbonation deterioration model

- **Governing Equations:** Chloride diffusion and carbonation can be described by Fick's 2nd Law of diffusion, $\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$.

Table 1: Solutions to Fick's 2nd Law for Chloride and Carbonation [3,4,5]

Chloride Content	Carbonation Front Depth
$C_L(x,t) = C_S\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$	$x_{ca}(t) = \sqrt{2\Delta c}\sqrt{\frac{D_{CO2}}{a}t}$

- **Goal:** Assess time to corrosion initiation with moving boundary
- **Current Preliminary Model:**
  - Chloride solely (overarching, progresses quicker than carbonation)
  - Determinate values for Chloride Diffusion and Surface Content
  - Numerically solving Fick's Second Law

DISCUSSION

- Carbonation induces steel reinforcement corrosion by accelerating chloride ion penetration into concrete
- Multiple deterioration processes act simultaneously and therefore should not be analyzed separately
- A probabilistic model is the most prudent method to model chloride and carbonation deterioration since it captures the uncertainty of the input variables
- It is insufficient to only assess initiation phase in service life model as it predicts maintenance, but does not extend to ultimate structural failure

FUTURE WORK

- Incorporate carbonation front progression into probabilistic model for chloride penetration
- Integrate results from initiation phase model into corrosion model to assess cross-sectional area lost
- Utilize results in FE model of concrete pile to determine ultimate limit state of concrete structures affected by carbonation and chloride deterioration
  - Include material densification caused by carbonation into FEM code

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FURTHER INFORMATION

Contact: Sabine Loos, **loos.23@osu.edu**

Dr. Abdollah Shafieezadeh, **Shafieezadeh.1@osu.edu**

RAMSIS Risk Assessment and Management of Structural and Infrastructure Systems Lab

URL: https://ramsis.engineering.osu.edu/

ACKNOWLEDGMENTS

We would like to thank Daniel Schmuhl for his previous research concerning chloride induced corrosion and for his mentorship in OpenSees modeling methods.